32.2.3 The Flyback SPS

The last SPS we'll look at is the flyback topology. This power supply finds extensive use in consumer electronics ranging from laptop power supplies, to USB AC to DC converters, and even chargers for electric shavers.

A schematic of the flyback topology is seen below in Fig. 32.29. The input to the power supply is the AC line (hot [line] and neutral) so it's sometimes called an "off-line" supply. This AC voltage is rectified to generate a DC voltage V_S. This DC voltage is connected to the primary of a transformer and a switch. The switch provides control to regulate the output voltage. Before we start analyzing this topology let's make some comments and then do a quick review of transformer operation and modeling.

First notice that there are two grounds in the power supply, one associated with the AC line side and the other associated with the DC output. This is for safety. A user of the power supply gets power from V_{OUT}. If the users shorts V_{OUT} (a lower DC voltage) to ground the amount of current that can be supplied is limited because of the transformer. This isn't the case on the AC line side where significant current can be supplied.

Next one might wonder why we need the switch on the primary side of the transformer? Or, why do we need to rectify the AC to generate DC and then connect the DC to the primary of the transformer and a switch? Why not simply rectify the output of the transformer after the AC line is stepped down? The answer is simply that the size of transformer for an AC input at 50 or 60 Hz is much, much larger than the size of a transformer for a signal at, for example, 100 kHz. By using the switch we can increase the effective frequency of the input to the transformer and thus reduce the transformer's size. This is important to ensure small-size power supplies.

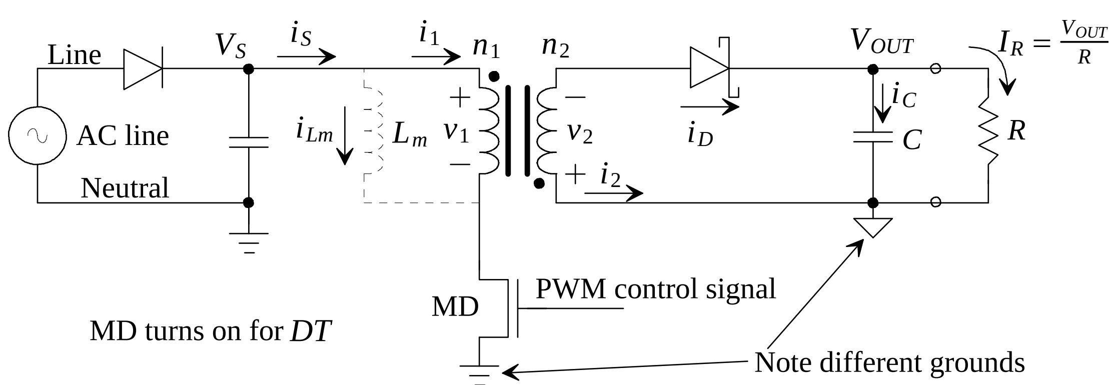

Figure 32.29 Flyback switching power supply.

Quick Review of Transformer Operation

Transformers are constructed by wrapping wire around a magnetic core (the core is indicated by the two bold lines in the middle of the transformer symbol). The number of times the wires are wrapped around the core is labeled n_1 and n_2 for the primary and secondary windings in Fig. 32.29 respectively. While we only show two sets of wires wrapped around the core, three or more wires can be wrapped around the core for multiple inputs and outputs. Further, while we use the terms "primary" and "secondary" note that the transformer can be flipped around so that the wire with n_2 turns is connected to V_S and the wire with n_1 turns is connected to the Schottky diode. The direction the wires are wrapped is indicated by the dots seen on the transformer symbol. The dots at the top, in the primary, and then the bottom, in the secondary, indicate that when v_1 goes up so too will v_2 as marked (they will be opposite in phase). When i_1 enters the dot on the primary it indicates the i_2 is leaving the dot on the secondary. The relationships between the voltages, currents, inductances (L_1 is the inductance of the primary and L_2 is the inductance of the secondary), and windings is as follows (assuming 100% magnetic coupling, $K = 1$, between L_1 and L_2)

$$\frac{v_1}{v_2} = \frac{i_2}{i_1} = \frac{n_1}{n_2} = \sqrt{\frac{L_1}{L_2}} \tag{32.56}$$

Notice the dotted L_m in Fig. 32.29. This is the magnetizing inductance of the transformer. This is the inductance that one would measure on the primary side of the transformer without anything connected to the secondary, that is, with the secondary open (which is why we have the secondary rectifying Schottky diode). In other words $L_m = L_1$, the inductance of the primary, with the secondary open. So, if MD turns on in Fig. 32.29 a current i_{Lm} (called a magnetizing current) flows in the magnetizing inductance L_M. Let's pause a moment and ask why we aren't talking about i_1? Well, let's suppose that i_1 does flow in the direction indicated in the figure. That would mean, per Eq. (32.56), a current i_2 would also flow, right? In this situation the diode is reverse biased and so i_2 is zero (and thus so too is i_1). When MD shuts off the magnetizing current wants to continue flowing so it flows backwards through the transformer, or $i_{Lm} = -i_1$. When this happens the diode turns on in the secondary of the transformer and the energy stored in the magnetizing inductance is supplied to the load, again modeled with a resistor R.

Operation of the Flyback SPS

Returning to the situation when MD is on (neglecting MD's on resistance as before) we can write

$$v_1 = V_S = L_m \frac{di_{Lm}}{dt} \tag{32.57}$$

Assuming MD is on for DT seconds, where as before D is the duty cycle, we can write

$$\Delta i_{Lm,up} = \frac{V_S \cdot DT}{L_m} \tag{32.58}$$

Again, as discussed above i_1 and i_2 are zero and the secondary rectifying Schottky diode is off when MD is on. The voltage across the primary is V_S which can be quite large. For example, if the AC input is 120V RMS. The peak voltage of the input sinewave is roughly 170V. Neglecting the diode drop of the AC rectifier on the primary side then V_S is also approximately 170V (so MD has to have a rated maximum V_{DS} in excess of this, more later). Even though there is no current flowing in the secondary there is still a voltage on the secondary calculated using Eq. (32.56) (used to determine the required breakdown voltage of the Schottky diode).

Example 32.8

A transformer is designed where the inductance of the primary (nothing connected to the secondary) is 10 mH and the inductance of the secondary (nothing connected to the primary) is 50 μH. What is the turns ratio, n_1/n_2, of the transformer? If a 120V RMS sinewave modulated up to 100 kHz is connected to the primary what is the secondary voltage assuming 100% coupling? Assuming no load connected to the secondary how much current flows in the primary? If a 10 Ω load is connected to the secondary how much current flows in the primary? Use simulations to verify your hand calculations.

Using Eq. (32.56) we can determine the turns ratio

$$\frac{n_1}{n_2} = \sqrt{\frac{L_1}{L_2}} = \sqrt{\frac{10mH}{50\mu H}} = 14.14$$

With a 120V RMS signal connected to the primary, again using Eq. (32.56), the secondary voltage, v_2, is 120/14.14 or 8.51V RMS (peak voltage of the output sinewave, v_2, is 12V). With no load connected to the secondary (i_2 = 0) of the transformer the current that flows in the primary (the magnetizing inductance) has a peak amplitude of 170V/(2π100kHz·10mH) or 27 mA (= i_{Lm} which we can't differentiate from i_1, which is 0, in the simulation). Simulation results are seen in Fig. 32.30.

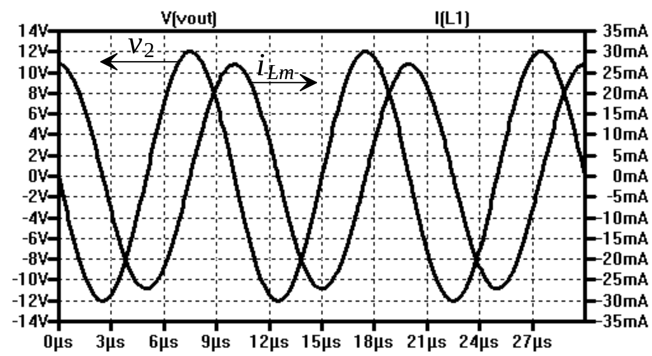

Figure 32.30 Showing secondary voltage and primary current, Ex. 32.8

When a 10 Ω load is connected to the secondary, the peak of i_2 is 12V/10Ω or 1.2A (the peak of v_2 is still 12V). The peak of i_1 is i_2/14.14 or 84.9 mA. Simulation results are seen in Fig. 32.31. The top trace shows $i_1 + i_{Lm}$ is 89 mA so let's show how to calculate this current. Notice the slight phase shift between the primary and secondary currents. The 10 Ω load, R, is reflected to the primary using Eq. (32.56)

$$\frac{v_1}{i_1} = \underbrace{\frac{v_2}{i_2}}_{R} \cdot \left(\frac{n_1}{n_2}\right)^2 \qquad (32.59)$$

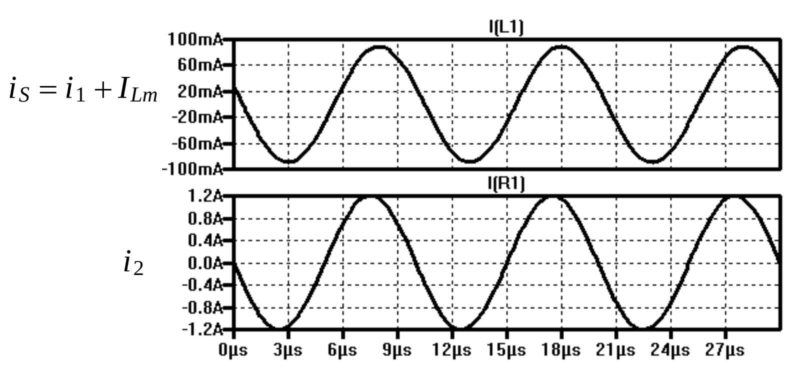

Figure 32.31 Showing the secondary and primary current, Ex. 32.8

Since, in this example, v_2/i_2 is 10Ω (= R) and $(n_1/n_2)^2$ is 200 the 10 Ω load is reflected to the primary as a 2 kΩ load (a resistive load in parallel with the 10 mH magnetizing inductance i_{Lm}). We can calculate the primary current using

$$i_1 + i_{Lm} = \frac{v_1}{R\cdot\left(\frac{n_1}{n_2}\right)^2 || j\omega L_m} = \frac{170}{2k||\, j(2\pi 100kHz)10mH} = \frac{170}{\frac{2{,}000\cdot j(6{,}280)}{2{,}000+j(6{,}280)}} = \frac{170(1+j3.14)}{0+j\cdot 6{,}280}$$

which has a magnitude of

$$\frac{170\cdot\sqrt{1^2+(3.14)^2}}{\sqrt{(0)^2+(6{,}280)^2}} = 89\text{ mA}$$

which is the simulated result. Note how, after reviewing this example, we could be less precise and simply look at the primary current as being only due to the load, that is, neglect the magnetizing current. This example is extremely important for understanding transformer operation, especially as it relates to a flyback SPS. ■

Using the numbers from this example in Eq. (32.58) with D = 0.3 results in

$$\Delta i_{Lm,up} = \frac{V_S\cdot DT}{L_m} = \frac{170\cdot 0.3\cdot 10\mu s}{10mH} = 51\ mA$$

As discussed earlier when MD shuts off i_{Lm} will be equal and opposite to i_1 (and i_S will go to zero abruptly, this is the one time current changes in an inductor instantaneously so make sure you understand the previous example). This results in the Schottky diode turning on (again as discussed earlier) so that, neglecting the diode forward voltage drop, $-v_2 = V_{OUT}$ and thus v_1 goes to $-V_{OUT}(n_1/n_2)$ (and so the maximum V_{DS} value needed for the MOSFET is $V_S + V_{OUT}(n_1/n_2)$, this is important). The change in the magnetizing current, when MD is off, can then be written, knowing that MD is off for $(1-D)T$ seconds, as

$$-\Delta i_{Lm,dwn} = \frac{-V_{OUT}\cdot(1-D)T}{L_m}\cdot\left(\frac{n_1}{n_2}\right) \qquad (32.60)$$

Knowing, as done for the buck and boost SPSs, the net change in these currents is zero

$$\Delta i_{Lm,up} - \Delta i_{Lm,dwn} = 0 = \frac{V_S\cdot DT}{L_m} - \frac{V_{OUT}\cdot(1-D)T}{L_m}\cdot\left(\frac{n_1}{n_2}\right) \qquad (32.61)$$

we can then relate the DC input, V_S, and to the DC output, V_{OUT}, in a flyback SPS

$$V_{OUT} = V_S\cdot\left(\frac{D}{1-D}\right)\left(\frac{n_2}{n_1}\right) \qquad (32.62)$$

Like the boost SPS, as D approaches 1 the output voltage can grow without bound even if the power supply isn't, or is, supplying power (current). For this reason flyback power controllers, those generating the PWM control signal in Fig. 32.29, are designed to have a maximum duty cycle.

Lastly, calculating the filter capacitor C follows the same procedure used for the boost converter so Eq. (32.53) can be used.

Example 32.9

Using the transformer from Ex. 32.8 with an input source, V_S, of 170 V design a 5V power supply using the flyback SPS topology that can supply 1A of current.

At this point the design consists of selecting the duty cycle, D, and the filter capacitor, C. Setting V_{OUT} to 5V in Eq. (32.62) results in D of roughly 0.3. The minimum value of R that models the load is calculated as R = 5V/1A or 5 Ω. Assuming we want no more than 10 mV of variation on the 5 V DC output we can determine C using Eq. (32.53)

$$C = \frac{0.3}{5 \cdot 100k \cdot (0.01/5)} = 300\ \mu F$$

Figure 32.32 shows the simulation results for the flyback converter driving a 5 Ω load. In this figure we show the start-up transient, just to be a bit different than the previous simulations which only showed a portion of the simulation. Note that if we increase the load the output voltage will go up a bit. In other words we aren't regulating the output. The next section provides a brief introduction to design of SPS control loops, which are used with the output stages we've covered in this, and the previous two, sections for regulating the output voltage of a power supply. ■

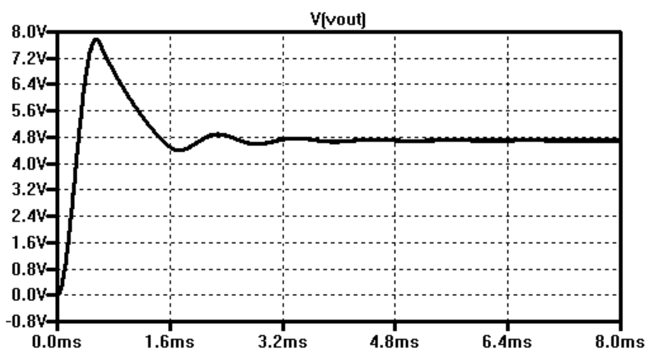

Figure 32.32 Simulating the flyback converter in Ex. 32.9 supplying energy to a 5 ohm load.

32.2.4 Pulse Width Modulation: A Control Loop Example

A pulse-width modulation (PWM) control circuit is seen below in Fig. 32.33. The goal of this circuit is to supply a PWM control signal at a frequency f (= $1/T$) with a duty cycle, D, that ensures that the output voltage of the SPS is regulated to the right value with changes in the load, V_S, temperature, etc. Before getting into the design procedures let's give an example. Let's assume that the output, V_{OUT}, of the SPS is to be regulated to 2.5V.

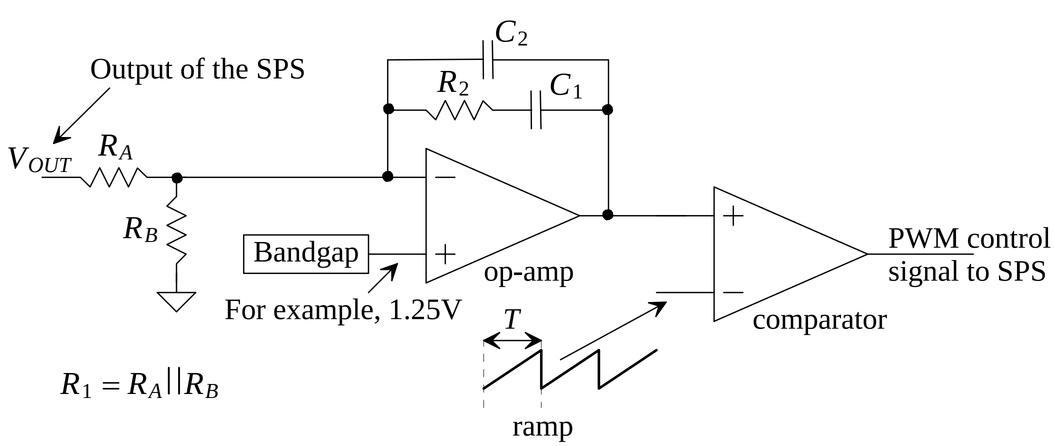

Figure 32.33 Pulse-Width Modulation (PWM) control circuit.